CO_2CARE

CO_2 SITE CLOSURE ASSESSMENT RESEARCH

Best Practice Guidelines summary

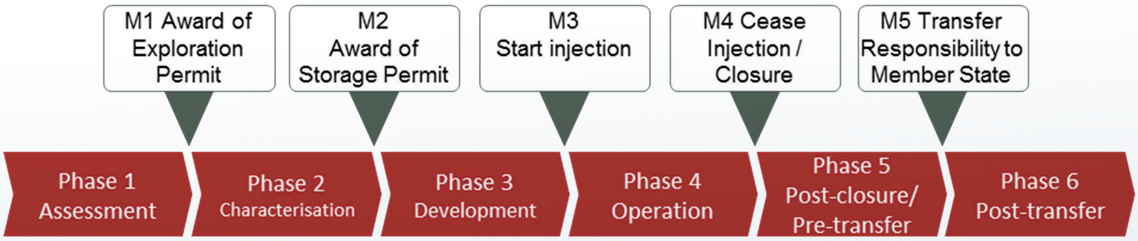
CO_2CARE has supported the large-scale implementation of CO_2 Capture and Storage (CCS) technology by developing best practice guidelines for a specific part of the chain: **CO_2 storage site abandonment**.

To guarantee the safe and long-term storage of CO_2, three main requirements or 'high-level' criteria, must be demonstrated*:

High level criteria

- No detectable leakage
- Observed behaviour of the injected CO_2 conforms to the modelled behaviour
- Storage site is evolving towards a situation of long-term stability

CO_2CARE has identified and delivered technologies and procedures to guarantee that these criteria can be met, thus ensuring the post-closure safety and long-term stability of storage sites. CO_2 Storage Life Cycle can be broken down into phases and milestones*.


M1 Award of Exploration Permit
M2 Award of Storage Permit
M3 Start injection
M4 Cease Injection / Closure
M5 Transfer Responsibility to Member State

Phase 1 Assessment
Phase 2 Characterisation
Phase 3 Development
Phase 4 Operation
Phase 5 Post-closure/ Pre-transfer
Phase 6 Post-transfer

CO_2CARE research covers phases 5 and 6 after the end of CO_2 injection. Ultimately, CO_2CARE has formulated robust procedures for site abandonment that will ensure long-term integrity of the storage complex.

CO_2CARE research has focussed on the industrial-scale CO_2 injection operation at Sleipner in the Norwegian North Sea and the pilot-scale sites K12-B, offshore of the Netherlands, and Ketzin in Germany and draws also on experiences from storage sites worldwide. A primary aim is to develop Best Practice protocols and methodologies for the safe and secure closure and abandonment of large-scale CO_2 storage sites.

This brochure summarises the key findings from the CO_2CARE Best Practice Guidelines document which is available on the CO_2CARE website. The brochure is laid out as two parallel themes. The main 'white' column summarises best practice for risk management, well abandonment and post-closure reservoir management. The secondary 'blue' column summarises key best practice issues associated with the three high level requirements of the Directive: no detectable leakage, observed and modelled conformance and long-term stability.

(*) *Source: EC Guidance Document 3 'Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide'*

GFZ Helmholtz Centre Potsdam
Imperial College London
IFP Energies nouvelles
TNO innovation for life
BGS British Geological Survey Natural Environment Research Council
OGS
brgm Géosciences pour une Terre durable
GEUS
Uppsala Universitet
Air Liquide
RWE Vorweg gehen
Statoil
Shell
Vattenfall
Veolia Environnement
Alberta Innovates
University of Alberta
RITE
The University of Texas at Austin
Berkeley Lab
Battelle The Business of Innovation
CO2CRC
Total
GDF Suez

Seventh Framework Programme

CO_2CARE is grateful for the funding from the European Commission under the FP7 and from its industrial partners RWE, Statoil, Shell, Total, Vattenfall, and Veolia Environment.

Transfer of Liability
No detectable leakage

CO_2CARE has focussed on early detection of leakage (e.g. as soon as possible after CO_2 migrates out of the storage reservoir), such as might occur during post-closure monitoring.

We have assessed the leakage detection ability of 3D time-lapse seismics which can provide robust and uniform spatial coverage of the subsurface storage footprint, particularly in offshore situations. CO_2 accumulating in the overburden, either as sub-horizontal layers or sub-vertical 'chimneys' will lead to changes in reflectivity and time-shifts which are extremely sensitive to even small amounts of CO_2. Detection thresholds are highly site and position dependent, varying with reservoir depth, seismic quality and repeatability, geology, CO_2 properties and also with both the thickness and area of the CO_2 accumulation, and trade-offs therein. The time-lapse seismics at Sleipner can easily image accumulations of CO_2 at the top of the reservoir with masses of around 7000 tonnes, and have a statistically-determined detection threshold of around 2100 tonnes. Detection thresholds in the overburden are likely to be even lower, perhaps as small as a few hundred tonnes in favourable circumstances.

Early detection of leakage precursors is recommended practice as it gives time for suitable mitigation actions to be implemented before leakage, as formally defined (migration of CO_2 out of the Storage Complex), actually occurs.

All leakage monitoring systems have a finite (and site-specific) CO_2 detection capability, so the question arises as to the usefulness of the term 'no detectable leakage'. Detection capability can be equated to the maximum allowable leakage rate consistent with a storage site meeting its greenhouse gas emissions mitigation objective. A number of studies have suggested that leakage rates around 0.01% per year or less would ensure effective mitigation performance. So for a hypothetical large-scale storage project, injecting around 100 Mt of CO_2, the detection capability of the Sleipner seismics would be some two orders of magnitude below the effective mitigation leakage limit. 'No detected leakage' in such a situation would therefore provide robust confirmation that the site was meetings its emissions mitigation objectives.

It is recommended therefore that regulators use the term 'no detectable leakage' in the context of whether a site is performing effectively in terms of emissions mitigation.

Managing risk associated with storage site closure

To ensure that all the measures required for site long term safety and sustainability are implemented effectively, CO_2CARE recommends subdivision of the Post-closure/ Pre-Transfer and Post- transfer stages of the project life cycle into shorter sub-phases. Linked to these we propose a set of site closure milestones (SCMs) to be fulfilled in chronological order before site closure and, subsequently, transfer of the storage site to the Competent Authority.

Site-Closure Milestone (SCM)	Description	Sub-phase	Phase/ Moment
0	Specify models and monitoring selected for conformity check	Final Operation	Phase 4 (Operational)
1	Check model/monitoring conformity during final operational phase; if necessary update models		
2	Provisional post-closure plan updated		
3	Final (updated) post-closure plan submitted		
4	Final (updated) post-closure plan approved		
5	Site Closure	-	Site Closure
6	Optional update of risk management plan	Post-Closure	Phase 5 (Post-Closure/Pre-Transfer)
7	Model check-update loop terminates		
8	Models and monitoring data are within acceptable conformance after M7 has been reached without significant adjustment (e.g. for a minimum period of five years)		
9	Optional final update of risk management plan		
10	Evidence of absence of leakage presented to Competent Authority		
11	Effectiveness of storage concept: Evolution to long-term stability demonstrated		
11a	Pressure evolution demonstrated to match model prediction		
11b	Plume movement is demonstrated to be an acceptable match to model predictions (within tolerances)		
11c	Optional verification of other parameters/features related to the storage concept		
12	Final wellbore check before abandonment (final well logging)		
13	Draft report for transfer of responsibility submitted	Pre-Transfer	
14	Report approved		
15	Surface facilities removed		
16	Well abandonment accepted		
17	Transfer of responsibility approved and accomplished	-	Site Transfer

Site-closure milestones leading to the transfer of responsibility according to the EU Storage Directive.

We have also developed a set of criteria, high-level, risk based and technical, that can be applied to determine whether each of the site closure milestones has been reached.

We recommend that the Competent Authority and the storage site operator should agree a priori on the specific conditions for deviations from the predicted site behaviour that will trigger corrective measures, as these will depend on site-specific characteristics. These might be based on quantitative threshold values such as the measured difference, or offset, between predicted and measured performance measures. Finally we recommend that criteria for long term safety and security of the site should be based purely on technical considerations and should not be linked to prescriptive time spans. A post-operational CO_2 storage site should be sealed as soon as possible after all criteria for the transfer have been fulfilled and the Competent Authority is satisfied that the long-term integrity of the storage site is assured.

R-type criteria	Description of criteria	EC requirements and Site Closure Milestones	Sub-Phase
R1	Pressure evolution conforms to the reservoir models	Absence of leakage (SCM10 & SCM12)	Post-Closure
R2	No detectable indication of leakage by monitoring measures		
R3	Evidence for the location of the CO_2-plume within the storage site by periodic seismic surveys or other appropriate measures		
R4	Leakage has not been detected for at least 10 years, this period may include the operational phase		
R5	Well integrity is checked directly before abandonment according to best practices		
R6	Model recalibration iteration loop ends and model recalibration not required any more	Conformity of Monitoring data and model predictions (SCM7 & SCM8)	
R7	Model recalibration iteration loop ended at least five years ago		
R8	Pressure is developing towards an equilibrium pressure and according to models	Site evolvement towards long term stability (SCM11)	
R9	Plume movement is matching model predictions		
R10	Plume is not moving out of the storage site, confirmed by modelling and monitoring		
R11	Optional verification of other parameters/features related to the storage concept		

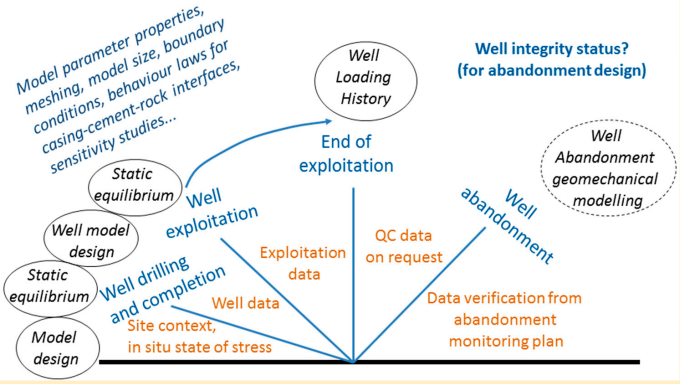
List of the criteria derived from Risk Management Plan (R-type criteria).

Well abandonment

One of the key requirements for the long term safety and security of geological CO_2 storage is that any wells contacted by the stored carbon dioxide should not leak; it is clear that the quality of the original wellbore construction is the main factor in ensuring long-term wellbore integrity.

To assess whether wellbores will have been susceptible to additional damage or degradation during the CO_2 injection operation, it is advisable to assess their geomechanical and geochemical history. A scheme, focussing on mechanical effects, was developed in CO_2CARE to identify wellbore weaknesses at end of the storage operation and to inform the risk management plan.

Longer-term prediction of wellbore performance remains challenging and depends on various types of predictive modelling and experimental or analogue information. Laboratory experiments conducted by CO_2CARE exposed typical well casing, cement and rock materials to CO_2 for periods up to several years. Results indicate that for typical storage conditions, cement carbonation and steel corrosion reactions can cause porosity plugging in the rocks and wellbore annuli, tending to retard or prevent CO_2 migration up, or alongside, the wellbore.



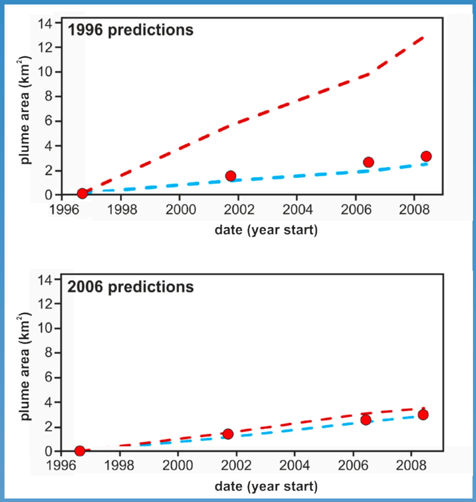
Modelling workflows for well mechanical history (left) and abandonment design and completion (right).

Transfer of Liability
Predicted and observed conformance

Demonstrating conformity between predictive models of reservoir performance and monitoring observations is technically challenging because a unique and perfect match is near-impossible to achieve. CO_2CARE research has focused therefore on showing that:

- Provided storage processes are well understood, models and observations will converge systematically as progressively more monitoring data is acquired.
- As uncertainties reduce, predictive capability improves, but focus must still be maintained on the less likely 'end-member' model scenarios to avoid the possibiltiy of unextpected or divergent future outcomes.
- At site abandonment, predictive models calibrated by monitoring data can reduce the uncertainty envelope sufficiently for unexpected or divergent outcomes to be ruled out.

Work at Sleipner shows clearly that as more monitoring data becomes available, conformance improves dramatically, with a progressive decrease in uncertainty with time, and improved accuracy of future predictions.

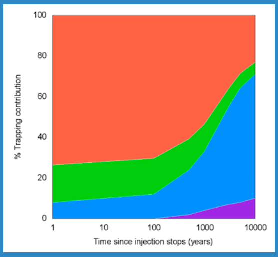


Predictions of plume footprint area showing upper (brown) and lower (blue) limits, based on datasets available in 1996 (baseline) and 2006.

Given the difficulty of producing a unique or perfect match between modelled and monitored data, we recommend that regulators should set conformance criteria at realistic levels, focussing on progressive reduction of uncertainty with time and demonstration that the fundamental site-specific storage processes are understood.

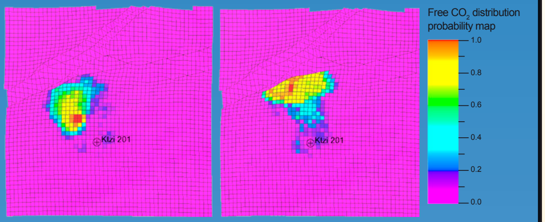
Transfer of Liability
Long term stability

Demonstrating that a site is moving towards a state of long-term stability is difficult due to the lack of long-term observational evidence from available storage projects. It is accepted that four CO_2 trapping processes, operating on progressively longer time-scales, are key to the process of site stabilization.



Trapping processes. Red: Structural/ stratigraphic trapping – potential leakage risk; Green: CO_2 residually trapped in pore space – very low leakage risk; Blue: CO_2 dissolved in brine – extremely low leakage risk; Purple: CO_2 trapped as mineral phase – no leakage risk.

The onset times and relative importance of each process vary with conditions and site-specific modelling is required. For the initial, structural trapping phase, CO_2CARE has modelled CO_2 distributions for a range of reservoir properties at Ketzin for periods up to 500 years into the future. Such predictions are useful to prioritise monitoring and risk management activities during the post-closure period.



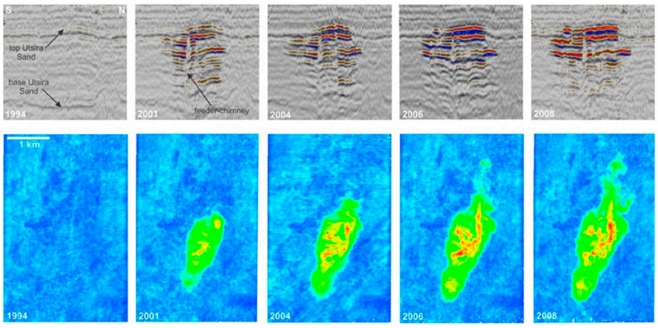
Free CO_2 distribution probability maps (area 5km x 5km) at the top layer of the Ketzin reservoir, showing the most likely far-field plume behaviour in 2018 (left) and in 2513 (right).

Predictive modelling of the longer-term processes is subject to significant uncertainty, so full use of additional analogue information is important to develop a logical case for site stabilization. Use should be made of monitoring data from sites already in the post-closure period (e.g. Nagaoka), experimental data and relevant geological analogues which demonstrate stabilization processes in similar circumstances and the time-scales on which they operate.

Post-closure reservoir management

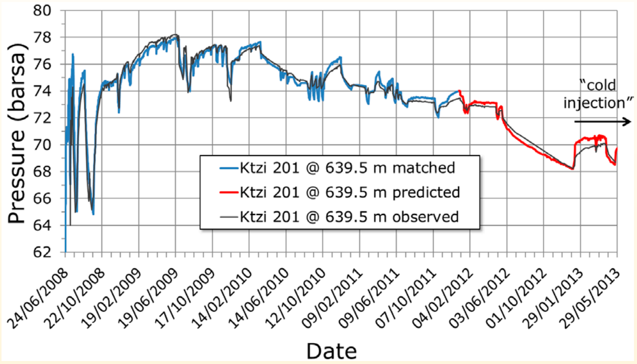
The main purpose of reservoir management after the cessation of CO_2 injection into a storage site (i.e. post-closure) is to demonstrate that the key regulatory requirements for transfer of storage site liability to the Competent Authority have been met. These are based around demonstrating understanding of reservoir processes, the ability to make robust predictions of future behaviour and providing assurance against leakage.

Migration of the CO_2 plume and reservoir pressures are the two key determinants of reservoir performance during the injection and post-immediate post-injection phases. At Sleipner and Ketzin, time-lapse 3D seismics have proved to be the key monitoring tool to track plume migration, providing high resolution images of the plume, its spatial footprint and detailed information for reliable predictive model calibration.



Time-lapse 3D seismics at Sleipner showing details of the CO_2 plume in cross-section (top) and development of the CO_2 footprint (bottom).

At Ketzin, K12-B and Rousse, down-hole pressure measurements have also proved to be a key performance indicator, providing insights into reservoir permeability and capacity, ensuring geomechanical stability and enabling robust predictions of future behaviour.



History-matching of modelled and observed reservoir pressures at Ketzin, showing accuracy of post-2011 prediction.

3D seismics and down-hole pressure measurements are proven technologies and have been the key monitoring tools for reservoir management at the CO_2CARE sites. It is likely that this will be the case for storage sites elsewhere, albeit with varying site-specific requirements. It is also worth stressing that the roughly two yearly repeat survey frequency at Sleipner mostly reflects the requirements for monitoring the deeper gas field. A dedicated monitoring programme for the CO_2 storage site would very likely involve a much lower time-lapse repeat frequency. Other tools are likely to be of complementary value in certain situations; down-hole logging and fluid sampling to characterise longer-term stabilization processes for example.

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November 2013—NERC-BGS (Debbie Rayner) Science Services